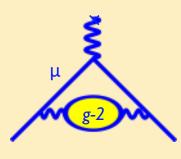




First Results from the Muon g-2 Experiment at Fermilab

Adam Lyon (Fermilab) on behalf of the Muon g-2 Collaboration University of Maryland/Johns Hopkins University HEP Seminar 14 April 2021



The New Muon g-2 Experiment at Fermilab

Adam Lyon (Fermilab/Scientific Computing Division)

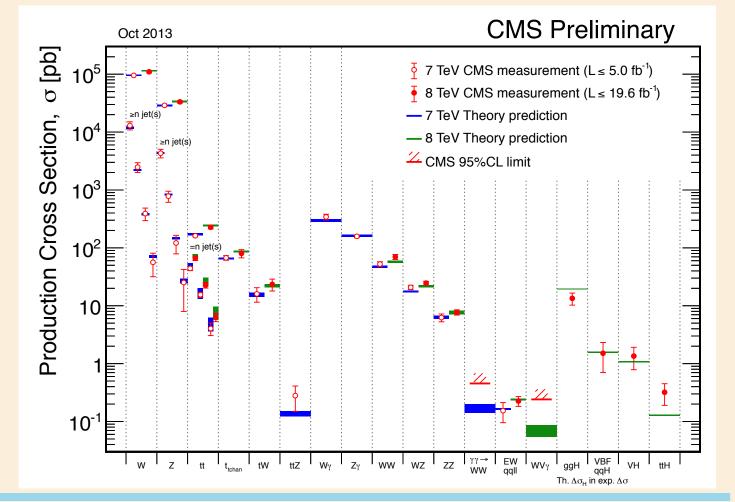
University of Maryland HEP Seminar May 1, 2013



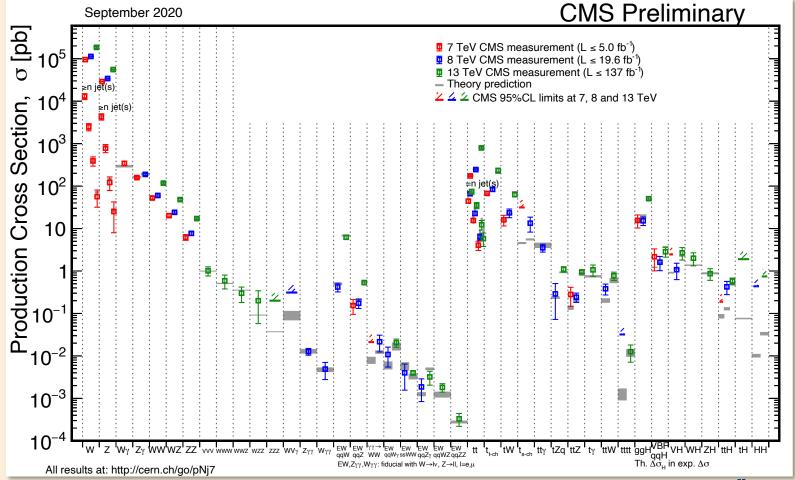
The Standard Model Quarks **Forces** Higgs boson

Leptons

Is this the whole picture?







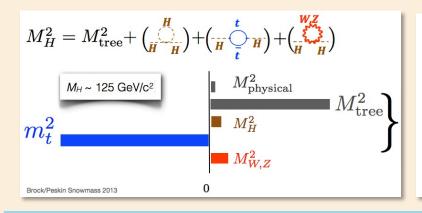


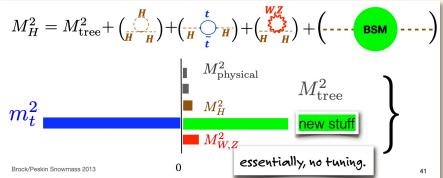
Why do we look beyond the SM?

... it doesn't predict everything we want:

 Gravity? Dark Matter? Dark Energy? Neutrino masses? Matter/antimatter asymmetry?

... and the SM contains some headaches that Beyond the SM may fix

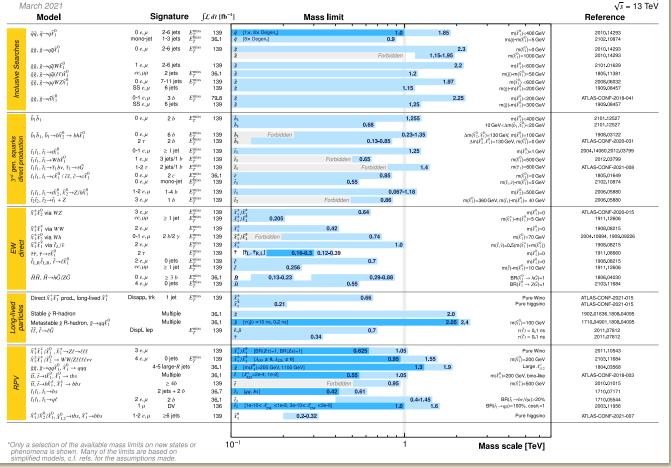






And we've looked for BSM

Supersymmetry



ATLAS SUSY Searches* - 95% CL Lower Limits



ATLAS Preliminary

And looked...

Contact Interactions

Dark Matter

R parity violating

Extra dimensions

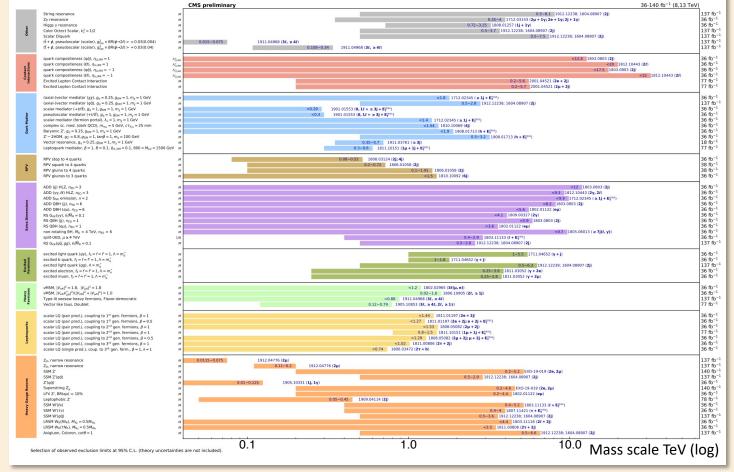
Excited Fermions

Heavy Fermions

Leptoquarks

Heavy Gauge Bosons

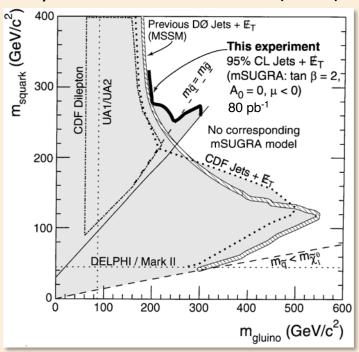




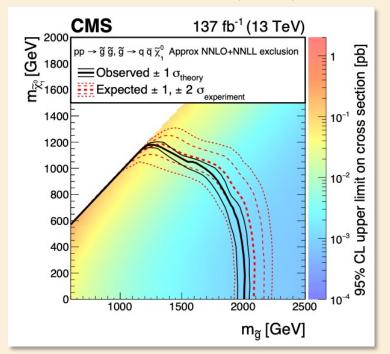


I've looked too...

My Run 1 D0 Thesis result (1999)



Latest CMS result (2020)



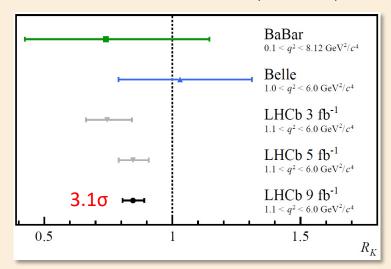


Still looking...

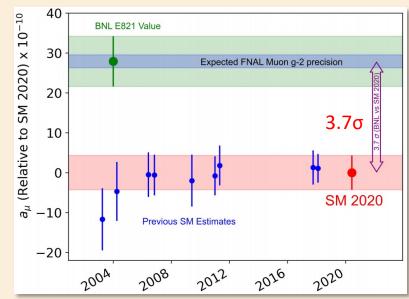
No direct confirmation of a Beyond the Standard Model theory and precious few experimental hints to guide us. Here are maybe two...

1) LHCb test of lepton flavor universality

(March 2021)
$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \stackrel{\text{SM}}{=} 1$$



2) Muon *g-2*





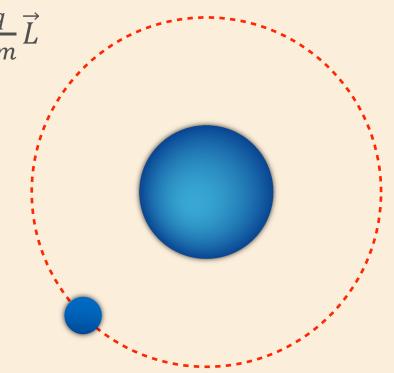
The "g-factor" basics

Orbiting charged particle:
$$\overrightarrow{\mu_L} = \overrightarrow{I}A = \frac{q}{2m}\overrightarrow{L}$$

Spin ½ particle has an intrinsic magnetic moment:

$$\overrightarrow{\mu_S} = g \frac{q}{2m} \vec{S}$$

For classical systems, g = 1

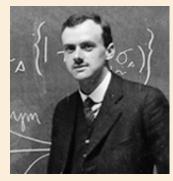


For the electron, g = 2 was known from Stern-Gerlach and spectroscopy experiments



Why does g = 2?

Predicted theoretically by Dirac in 1928



$$\left(\gamma^{\nu}\left(p_{\nu} - \frac{e}{c}A_{\nu}\right) - mc\right)\psi = 0$$

$$i\frac{\partial\psi}{\partial t} = \left[\frac{1}{2m}(\vec{p} - e\vec{A})^2 - 2\frac{e}{2m}\vec{S} \cdot \vec{B}\right]\psi$$

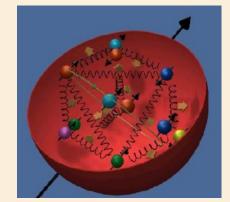
Paul Dirac

An aside: in 1933, for protons g = 5.6,

neutron g = -3.8

Protons and neutrons are not like electrons!

For the <u>electron</u>, *g* remained = 2 for twenty years





Why is g > 2?

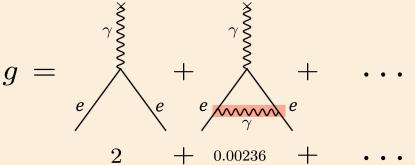
1948: Foley & Kusch in spectroscopy measure $g_e = 2.00238(10)$ 0.12%

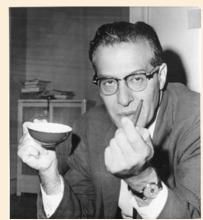
Write as the anomalous magnetic moment $a \equiv \frac{g-2}{2}$, $a_e = 0.00119(5)$

Soon after this, Schwinger calculates first order QED correction

$$a_e = \frac{\alpha}{2\pi} = 0.00116$$

Quantum Corrections





Julian Schwinger
"His laboratory is his ballpoint pen"



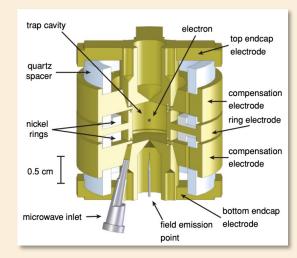
Electrons vs. Muons

Currently: $a_e = 0.001 \ 159 \ 652 \ 180 \ 73(28)$... a 0.28 ppt result! Hanneke et. al., PRA 83, 052122 (2011)

Difference from QED prediction is $|\delta a_e| < 9 \times 10^{-13}$ Excellent agreement

But hadronic and weak contributions to a_e are tiny

$$a_{e,hadronic} = 1.671(19) \times 10^{-12}$$
 $a_{e,weak} = 0.030(01) \times 10^{-12}$ Gabrielse et. al., PRL 97, 030802 (2006)

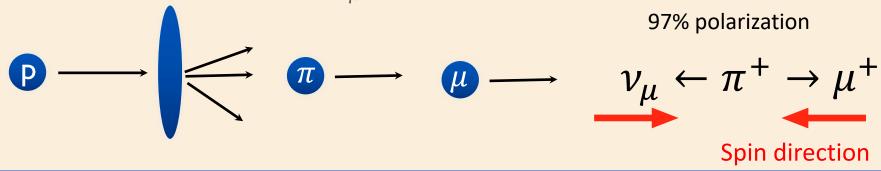


Sensitivity goes as $\left(m_{\mu}/m_{e}\right)^{2}\approx43~000$ So, look to Muons...



Controlling and measuring the muon spin

Production: Muons from $\pi^+ \to \mu^+ \nu_\mu$ are polarized



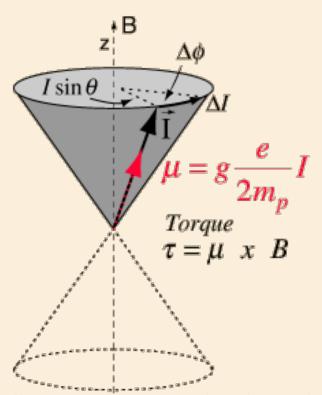
Decay: "Self analyzing" $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_{\mu}$



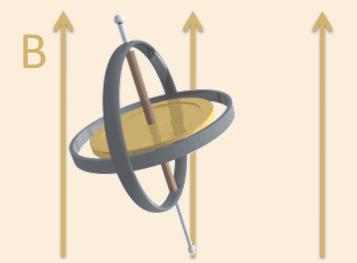
Highest energy positrons emitted along muon's **spin** direction



Muons at rest in a magnetic field – Larmor Precession



$$\omega_s = g \frac{eB}{2mc}$$

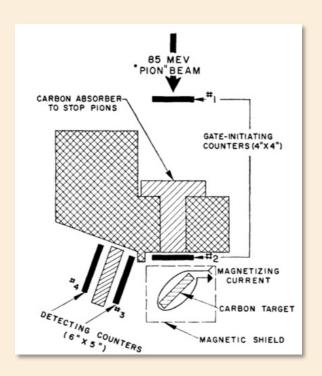


http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/larmor.html

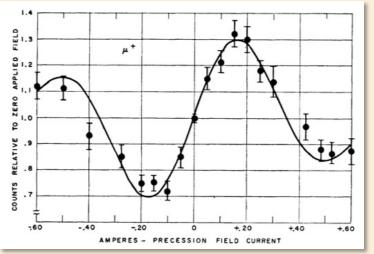


First experiment for muon magnetic moment

1957: Garwin, Lederman, Weinrich at Nevis (confirmed Yang & Lee parity violation)



Direct measurement of g (asymmetry vs field)



$$g_{\mu} = 2.00 \pm 0.10$$
 Sw uncertainty

Muons behave like electrons

$$g_{\mu}=2.004\pm0.014~$$
 Cassels et. al. (Liverpool)



Subsequent Experiments

CERN I (1965) $a_{\mu} = 0.001 \ 162(5) \pm 4300 \ \mathrm{ppm}$ (Non-relativistic)

CERN II (1968) $a_{\mu} = 0.001 \ 166 \ 16(31) \ \pm 270 \ \mathrm{ppm}$ (storage ring)

 $p_{\pi} = 1.27 \text{ GeV}/c$

B = 1.7 T



CERN III (1969-79) $a_{\mu} = 0.001\ 165\ 924(8.5)\ \pm 7.3\ \mathrm{ppm}$ (storage ring) $p_{\pi} = 3.1\ \mathrm{GeV}/c$ $B = 1.47\ \mathrm{T}$ Large systematic due to magnet edges

BNL E821 (2001) $a_{\mu} = 0.001 \ 165 \ 920 \ 89(63) \ \pm 0.54 \ \mathrm{ppm}$ $B = 1.45 \ \mathrm{T}$



Muons moving in a magnetic field

Thomas (spin) precession

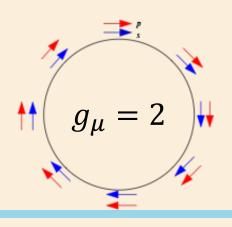
$$\omega_S = \frac{g_\mu e_B}{2m_\mu c} + (1 - \gamma) \frac{e_B}{m_\mu c_\gamma}$$

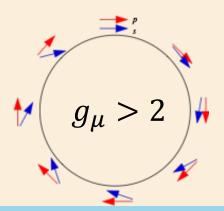
Cyclotron Frequency (Momentum precession)

$$\omega_{c} = \frac{eB}{m_{\mu}c\gamma}$$

A nice simplification

$$\omega_a \equiv \omega_S - \omega_C = \frac{g_{\mu} - 2}{2} \frac{eB}{m_{\mu}c} = a_{\mu} \frac{eB}{m_{\mu}c}$$





True for any ring and any muon momentum



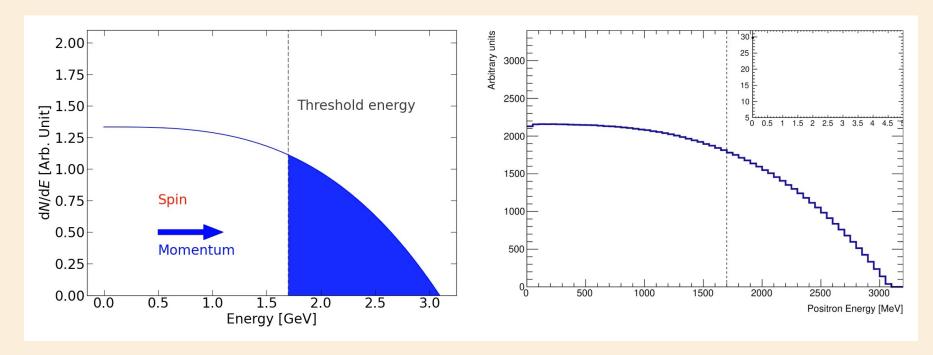
Spin and Momentum





What do we measure?

Remember, $\mu^+ \to e^+ \nu_\mu \overline{\nu}_e$ and highest energy positrons are in spin direction





Improvements and a miracle

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$$

Since $a_{\mu} \approx g_{\mu}/800$, measuring ω_a gives big improvement in precision than for muons at rest measuring g_{μ}

But a problem – how do we vertically confine the beam of muons in the ring? Introduce electrostatic quadrupoles. That leads to...

$$\vec{\omega}_{a} = -\frac{e}{mc} \left[a_{\mu} \vec{B} - a_{\mu} \left(\frac{\gamma}{\gamma + 1} \right) (\vec{\beta} \cdot \vec{B}) \vec{\beta} - \left(a_{\mu} - \frac{1}{\gamma^{2} - 1} \right) (\vec{\beta} \times \vec{E}) \right]$$

Can <u>mostly</u> cancel <u>last term</u> if we choose $\gamma = 29.3~(0.9994c)~p_{\mu} = 3.09~{\rm GeV}/c$ Vertical beam oscillation leads to muon decays out-of-plane (pitch correction)

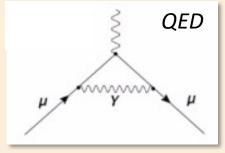


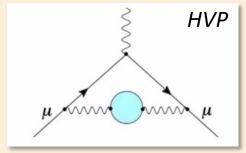
Theoretical interlude

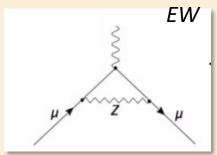
Muon g-2 Theory Initiative White Paper Phys. Rept. 887 (2020) 1-166

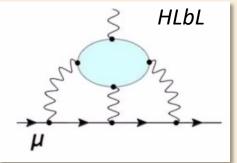
$$a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{EW} + a_{\mu}^{HVP} + a_{\mu}^{HLbL}$$

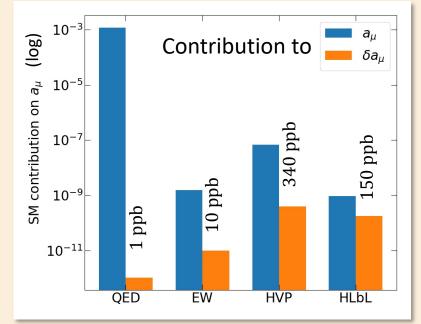
 $a_{\mu}^{SM} = 116\,591\,810(43) \times 10^{-11}$ 370 ppb





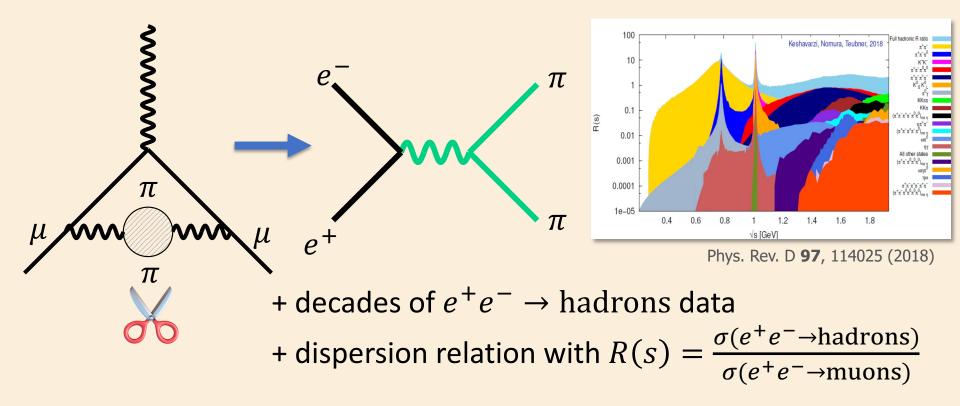








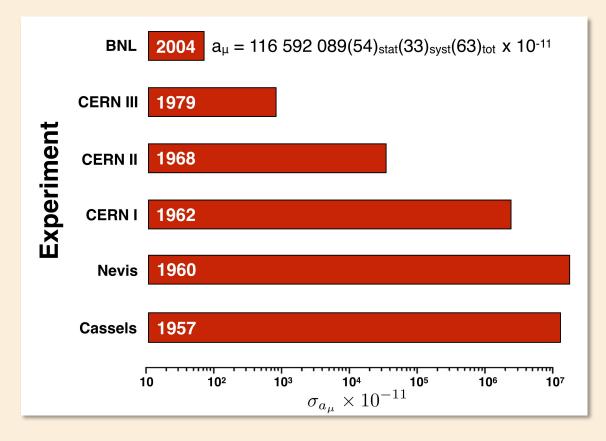
Data Driven HVP Calculation 340 ppb uncertainty (dominates)



New Lattice QCD efforts are interesting and looking promising



History



New Sensitivity

5 loops QED, EW

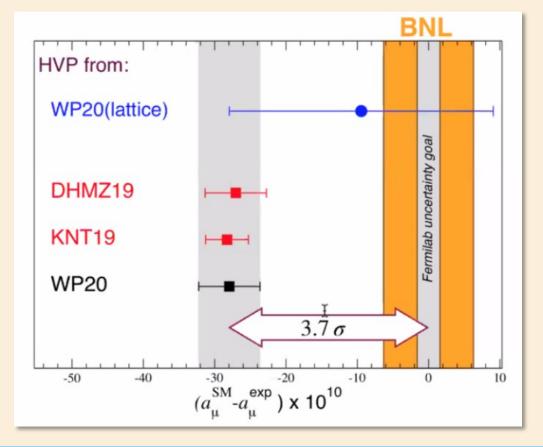
Hadronic

3 loops QED

2 loops QED



Situation prior to 4/7/2021





Goals of the Fermilab Experiment

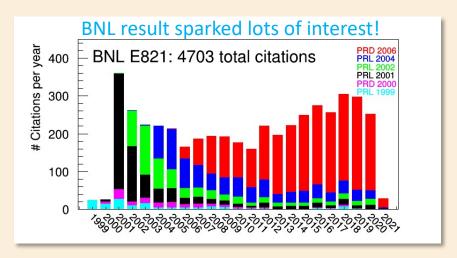
Do the experiment at Fermilab with more powerful and cleaner muon beam

Reduce the overall error by a factor of \sim 4 540 ppb \rightarrow 140 ppb

With 20x more muons, reduce the statistical uncertainty 460 ppb → 100 ppb

With many improvements, control systematics ~3x better 280 ppb → 100 ppb

Reuse the BNL ring (and recycle lots of other parts)







Muon g-2 collaboration



USA

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs

- Argonne
- Brookhaven
- Fermilab



China

Shanghai Jiao Tong



Germany

- Dresden
- Mainz



Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste



Udine

- Korea - CAPP/IBS
 - KAIST



Russia

- Budker/Novosibirsk
- JINR Dubna

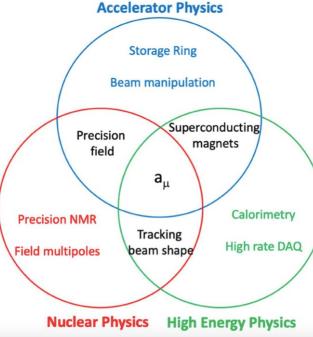


United Kingdom

- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London



>200 collaborators 35 institutions 7 countries



10 collaborators from BNL E821



The Big Move of the 50' diameter magnet (2013, 3000 mi, 3 months)











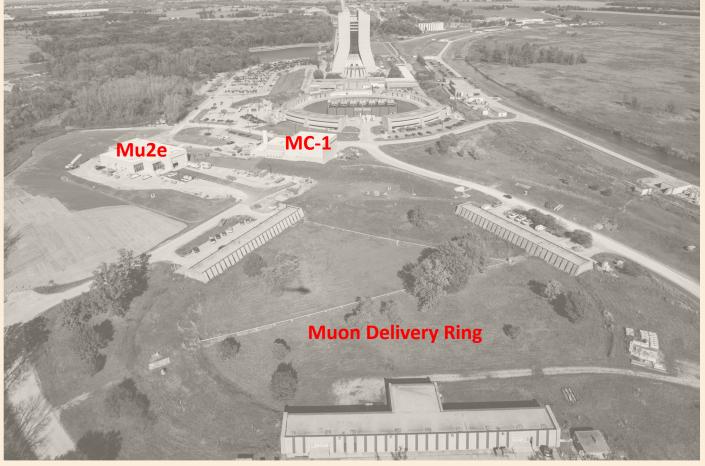


The Fermilab Muon Campus





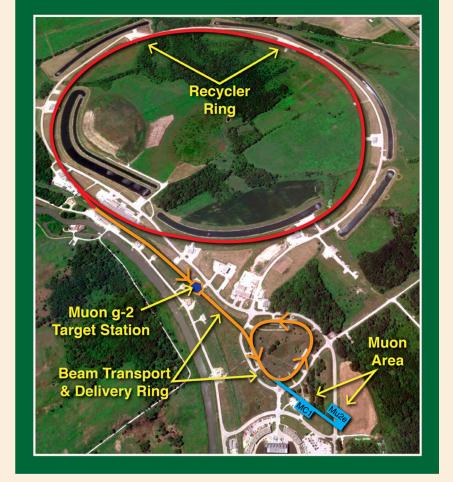
The Fermilab Muon Campus





Protons accelerated in Linac, Booster and into the Recycler

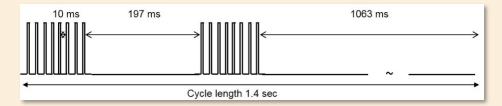
Repurposing the Tevatron anti-proton source





8 GeV protons from the Booster enter the Recycler Ring for re-bunching

16 bunches per 1.4 s cycle



Recycler is a permanent magnet ring that was used to retain the Tevatron anti-proton "stash" after a Tevatron shot to be "recycled" into the next shot



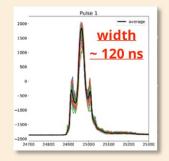


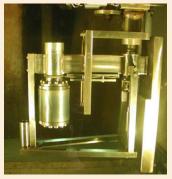
Repurposing the Tevatron anti-proton target

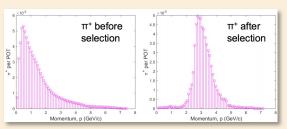
120 ns wide 8 GeV proton bunch

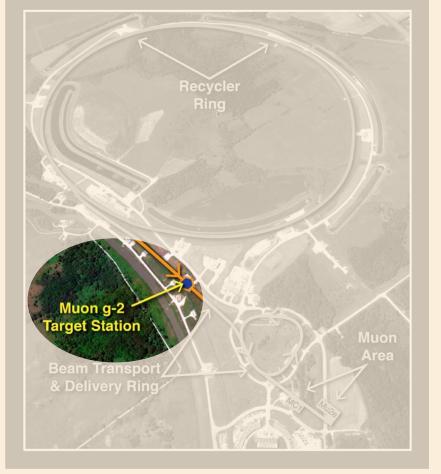
Inconel (nickel alloy) target Avg 9.84×10¹¹ protons on target

Lithium lens & pulsed magnet for 3.11 GeV π^+









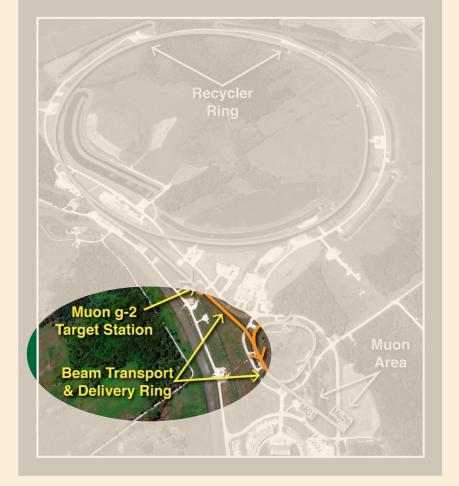


280 m transfer line for $\pi^+ \rightarrow \mu^+$

High quadrupole density

Accepts $\Delta p/p \approx \pm 4\%$ collecting 3.09 GeV muons from forward decays (longitudinally polarized)

~ 80% of pions decay in the transfer line 95% polarized

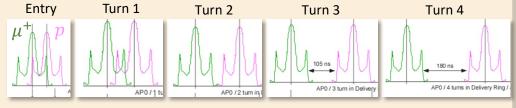




Delivery ring

Repurposing the anti-proton debuncher

4 turns around the 505 m circumference separate muons from hadrons



Protons are kicked out of the beam

Muons go to MC-1 and into the g-2 storage ring





Muon g-2 ring

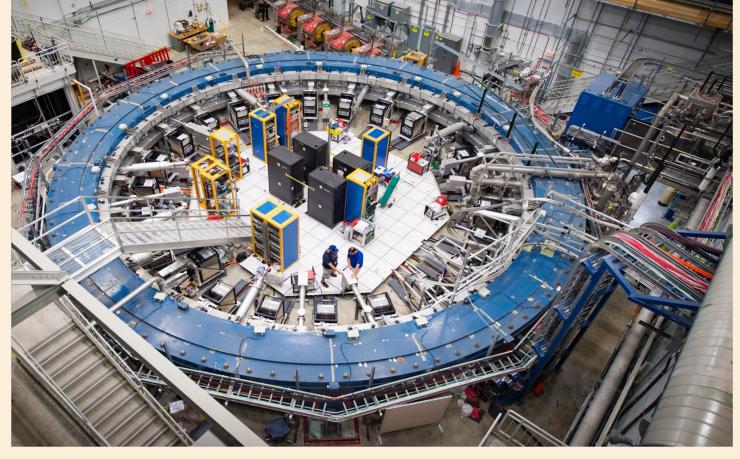
5 000 μ /fill stored (2% of injected)

 μ lifetime is ~ 64 μ s

Fill is 700 μ s (about 10 muon lifetimes)

Cyclotron period 149.2 ns

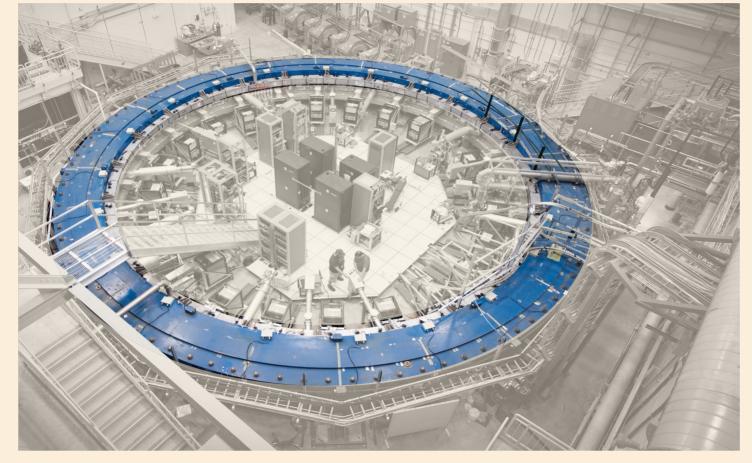
 $R_0 = 7.112 \text{ m}$





The Magnet

1.45 T Superferric magnet





Storage Ring Magnet

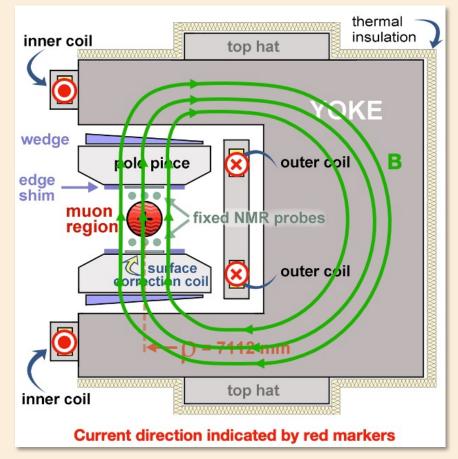
Iron yoke excited by superconducting coils

Pieces of asymmetric iron including wedges, laminations, and shims for shaping the filed

Storage region radius 4.5 cm

Magnet radius 7.112 m

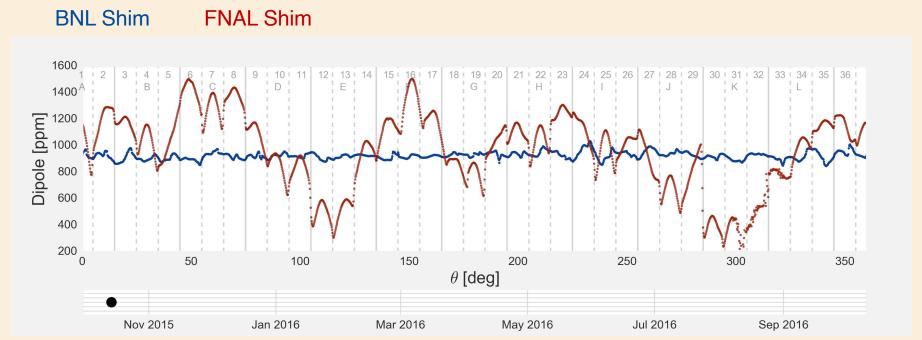
Shimmed to better than 50 ppm (3x better than Brookhaven)





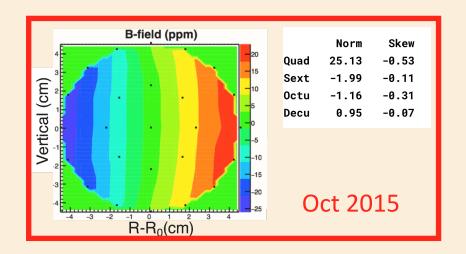
Shimming the magnet

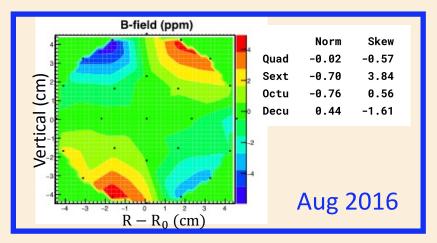
Took a year to interactively map, simulate, and adjust top hats, 864 wedges, 366 pole feet attached to 72 poles to $\pm 6~\mu m$ and **8424 foil shims**





Shimming the magnet







Inflector

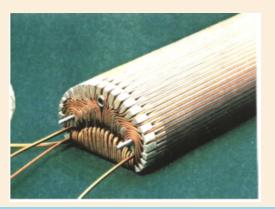


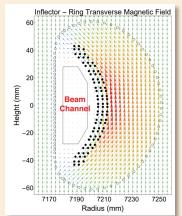


Entry & Inflector magnet









Muons need a field free section to enter the storage ring

Superconducting Inflector magnet cancels the 1.45 T field. Surrounded by superconducting sheet to avoid perturbing main magnet



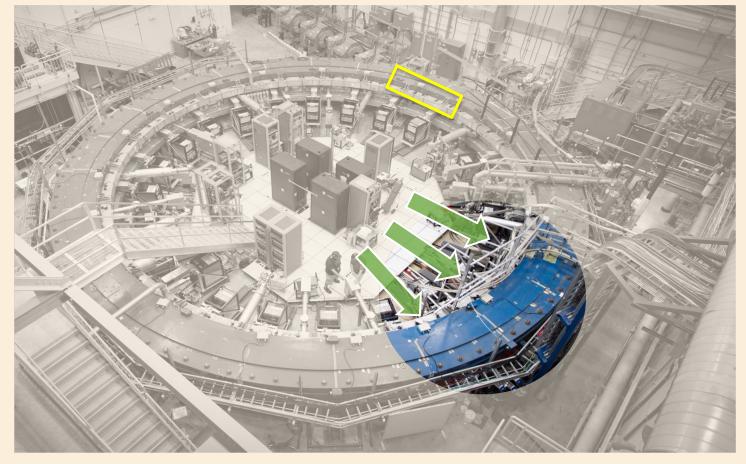
Kickers

Beam must be kicked 10 mrad

125 - 137 kV

~ 200 G field

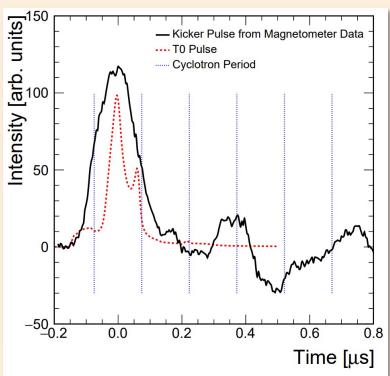
Must turn off within 149 ns (first turn)





Kickers





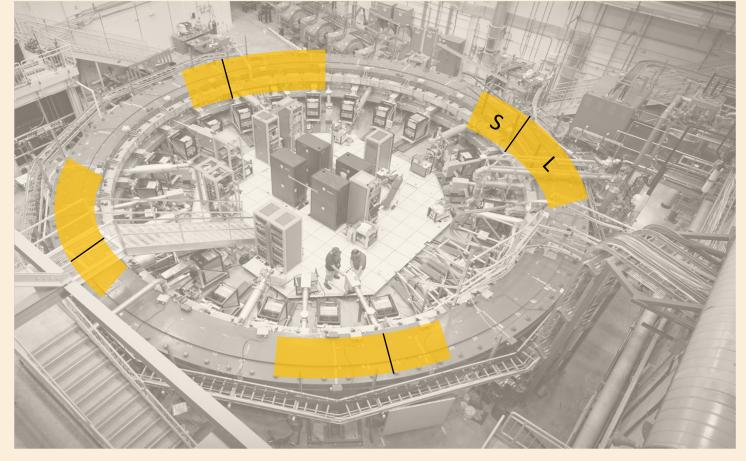


Quadrupoles

Electrostatic Quadrupoles (ESQ)

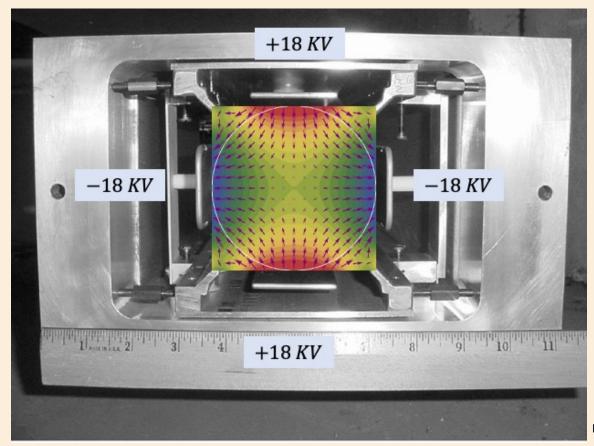
Vertical focusing

4 sections
each with short &
long
43% of
circumference





ESQ



Picture credit: Hogan Nguyen



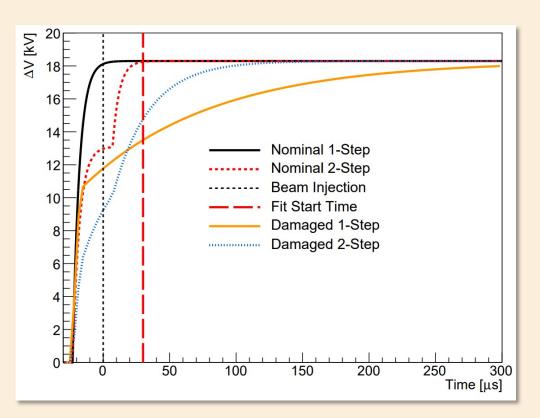
ESQ – Challenge in Run 1

Quadrupole plates are pulsed at 18.3 kV or 20.4 kV On for $700 \,\mu s$ fill then off

RC time constant designed to charge Quads in $\sim 5 \ \mu s$

But HV two resistors (of 32) were damaged and prolonged the turn on

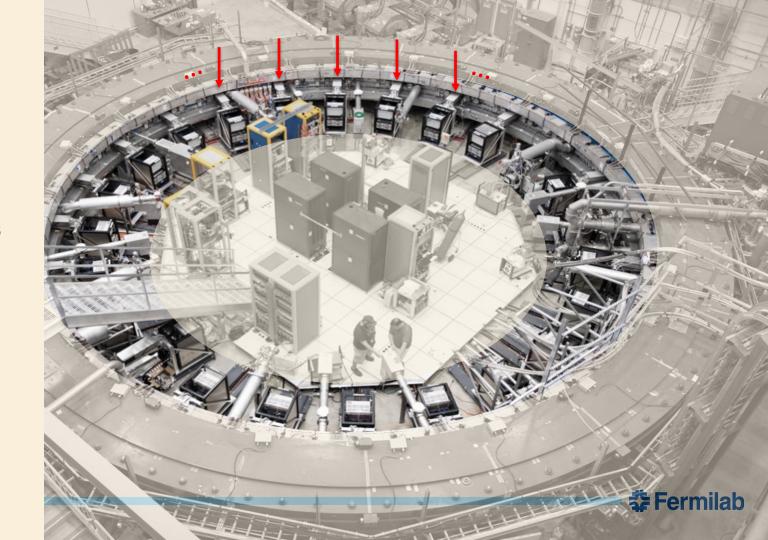
Implications for beam dynamics [Fixed after Run 1]



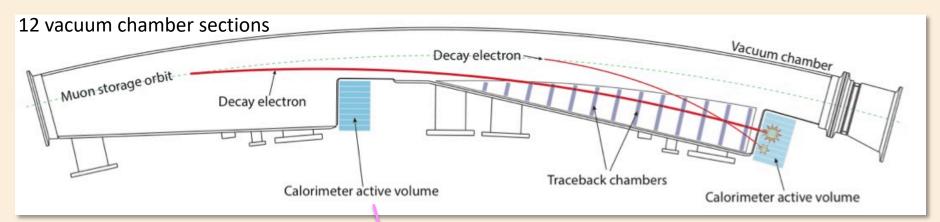


Calorimeters

24 Calorimeters for measuring positron energy



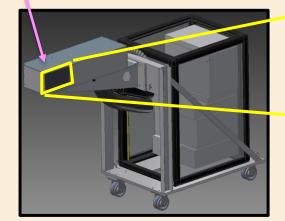
24 Calorimeters



9x6 array of PbF₂ crystals

Fast SiPM readout

800 Msamples/s waveform digitizers







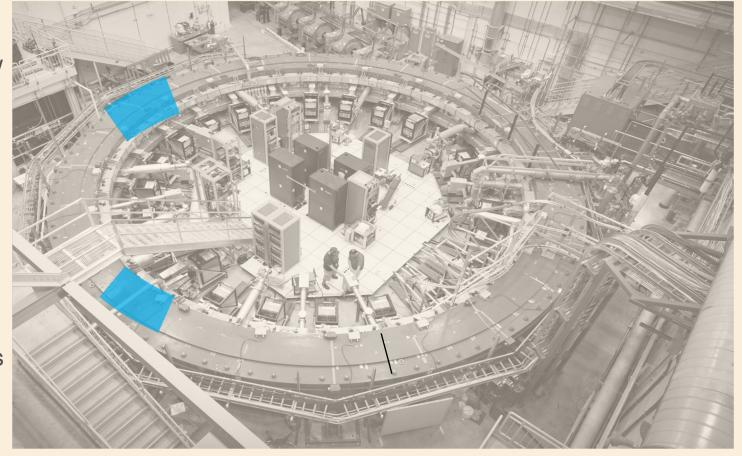
Trackers

2 stations of straw trackers *in vacuo*

Argon-Ethane

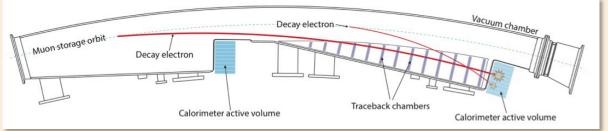
1500 channels

Gives spatial distribution and μ beam properties

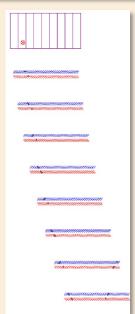




Straw tube trackers









Measuring the Field

We need to determine B to < 100 ppb

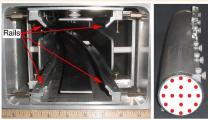
Use NMR probes to measure B in terms of proton precession frequency $\omega_{\mathcal{D}}$

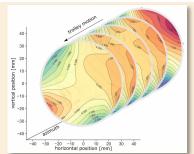
378 fixed probes monitored 24/7





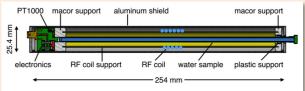
Trolley maps field every 3 days





$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$$

Trolley cross-calibrated to absolute probes Absolute probes all cross-calibrated in a 1.45 T MRI magnet at Argonne National Laboratory











us

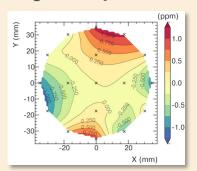
others (total known to ~ 24 ppb)

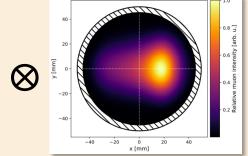
$$a_{\mu} = \frac{\omega_{a}}{B} \frac{m_{\mu}}{e} = \frac{\omega_{a}}{\widetilde{\omega}'_{p} (T_{r})} \frac{\mu}{\mu}$$

$$\frac{\omega_a}{\widetilde{\omega}_p'(T_r)} \frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

 ω_a : Muon spin precession frequency

 $\widetilde{\omega}_p'(T_r)$: Precession of protons in shielded water sample at 34.7 °C mapping the field and weighted by the muon spatial distribution





 $\widetilde{\omega}_p'$ (T): Proton Larmor precession frequency in a spherical water sample (temp dependence known to < 1 ppb/°C) Metroligia **13**, 179 (1977); **51**, 54 (2014); **20**, 81 (1984)

 $\mu_e(H)/\mu_p'(T_r)$: Measured to 10.5 ppb at $T_r=34.7~^{\circ}\mathrm{C}$ Metrologia 13, 179 (1977)

 $\mu_e/\mu_e(H)$: Bound-state QED (exact) Rev. Mod. Phys. 88 035009 (2016)

 m_{μ}/m_e : From muon hyperfine splitting (22 ppb) Phys. Rev. Lett. **82**, 711 (1999)

 $g_e/2$: Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)



Measuring a_{μ}

The quantities we measure:

$$\mathcal{R}'_{\mu} \equiv \frac{\omega_{a}}{\widetilde{\omega}'_{p} (T_{r})} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e} + C_{p} + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p} (x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + B_{k} + B_{q}\right)}$$

Dataset	# Days (Apr-Jun 2018)	Tune (n)	Kicker (kV)	# fills (10 ⁴)	# positrons (10 ⁹)
1a	3	0.108	130	151	0.92
1b	7	0.120	137	196	1.28
1c	9	0.120	132	333	1.98
1d	24	0.107	125	733	4.00

Total 8.2B positrons (~ 1.2x BNL) 6% of our target statistics



Reconstructing positrons

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\omega_{\boldsymbol{a}}^{\text{meas}} \left(1 + \frac{C_e}{c} + C_p + C_{ml} + C_{pa} \right) \right)$$

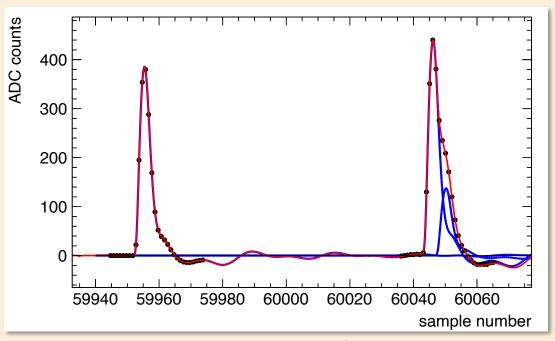
SiPM voltages → reconstructed positron energy in time

Find waveform islands with hits over threshold (50 MeV)

Fit waveforms from WFD to templates (template unique to each crystal)

Cluster across crystals to form positrons Two algorithms...

Local: individual crystals are fit & combined Global fit across multiple crystals



From Kevin Labe



Fitting wiggles

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\omega_{\alpha}^{\text{meas}} \left(1 + \frac{C_e}{c} + \frac{C_p}{c} + \frac{C_{ml}}{c} + \frac{C_{pa}}{c} \right) \right)$$

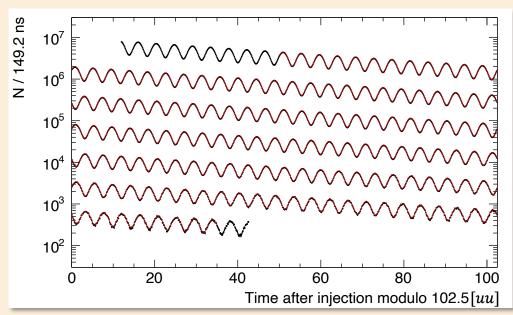
Fit to exponential decay and anomalous precession oscillation

$$N(t) = N_0 e^{-t/\tau_{\mu}} \left[1 + A(E_{\text{th}}) \cos(\omega_a t + \phi_0) \right]$$

Wiggle plot from counting positrons over threshold

Note that clock frequency is blinded (25 ppm) [uu] = unknown time unit

The fit $\chi^2/ndf = 9500/4150$ Why is the fit not good?

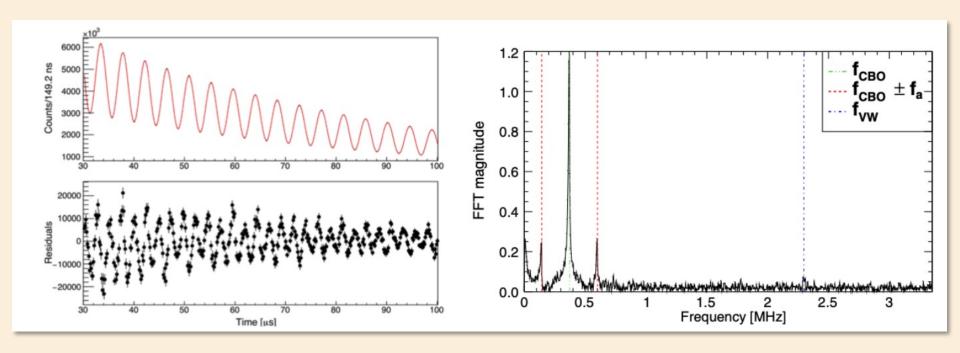




Other frequencies

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\frac{\boldsymbol{\omega_{a}^{\text{meas}}}}{\boldsymbol{\omega_{a}^{\prime}}} \left(1 + \frac{\boldsymbol{C_{e}} + \boldsymbol{C_{p}} + \boldsymbol{C_{ml}} + \boldsymbol{C_{pa}}}{\boldsymbol{\delta_{a}^{\prime}}} \right) \right)$$

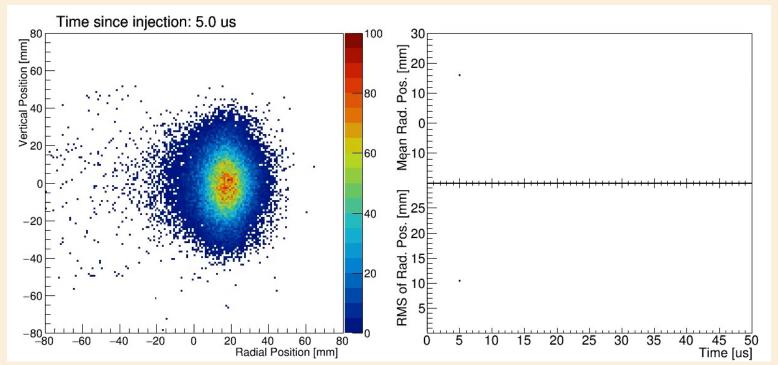
$$\chi^2/\text{ndf} = 9500/4150$$





Coherent Betatron Oscillation (CBO)

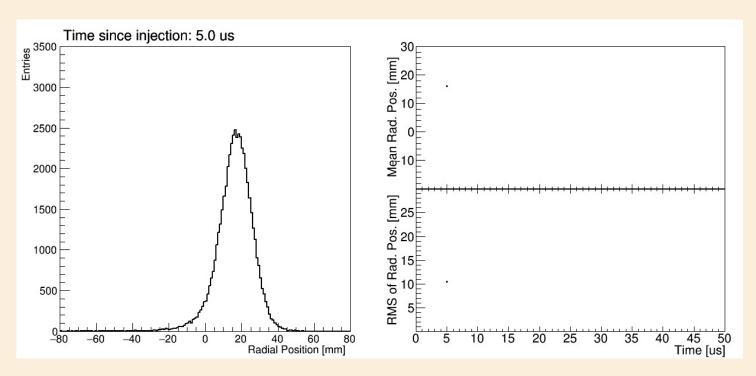
The muon beam "swims" and "breathes" Measured by trackers





Coherent Betatron Oscillation (CBO)

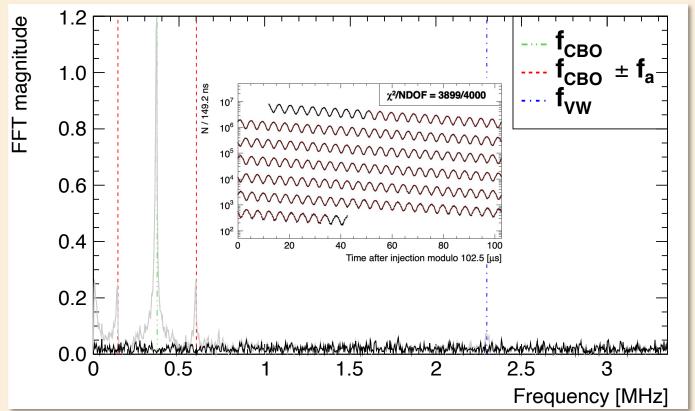
The muon beam "swims" and "breathes" Measured by trackers





21 parameter fit

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\omega_{\boldsymbol{\alpha}}^{\text{meas}} \left(1 + \frac{C_e}{e} + \frac{C_p}{e} + \frac{C_{ml}}{e} + \frac{C_{pa}}{e} \right) \right)$$





Four analysis techniques

Multiple analyses (with added software blinding)

• T:
$$\sum N(E_{e^+})$$
 $E_{e^+} > 1.7 \text{ GeV}$

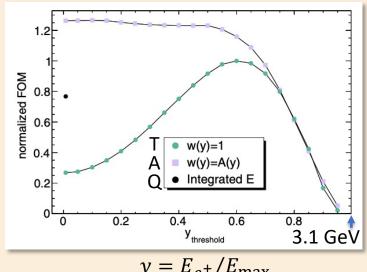
• **A**:
$$\sum A(E_{e^+})N(E_{e^+})$$
 $E_{e^+} > 1.0 \text{ GeV}$

- R: Ratio Method splits data into two time shifted sets and divide. Removes slow *t* dependence (exponential decay)
- Q: $\sum N(E_{e^+})$ No threshold (histograms from DAQ)

Two clustering algorithms; three pileup algorithms

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \quad \boldsymbol{\omega_{\alpha}^{meas}}}{f_{\text{calib}} \left\langle \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \right\rangle \left(1 + \frac{B_{k}}{B_{k}} + \frac{B_{q}}{B_{q}}\right)}$$

$$\sigma^2 \propto 1/N\langle A^2 \rangle_{E_{\rm th}}$$



$$y = E_{e^+}/E_{\text{max}}$$

4 A analyses were combined for result. Other 7 analyses were cross checks All 11 (highly correlated) analyses consistent



An important complication: Early-to-late effects

There is a potential problem in $N(t) = N_0 e^{-t/\tau_{\mu}} \cos(\omega_a t + \phi_0)$

Systematic effects sensitive to particle flux change from early in the fill to late Introduce an effective $\phi(t)$

$$\cos(\omega t + \phi_0) \to \cos(\omega t + \phi(t)) = \cos(\omega t + \phi_0 + \phi' t + \cdots) = \cos((\omega + \phi')t + \phi_0 + \cdots)$$

Failing to account for these effects would lead to a biased ω_a !!

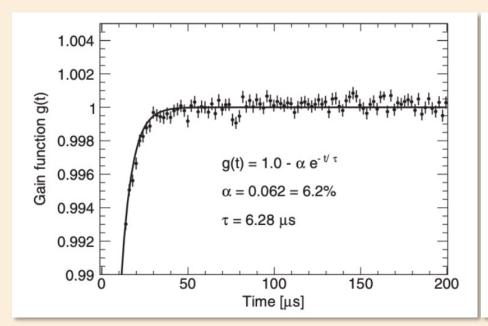
Possibilities: detector gain, pileup, lost muons, beam distortion

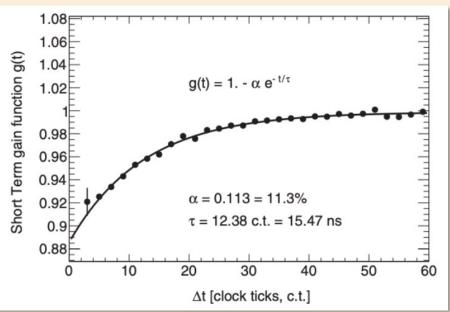


Early-to-late effects - Gain

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\frac{\omega_{\boldsymbol{a}}^{\text{meas}}}{\omega_{\boldsymbol{a}}^{\text{(1 + }C_{\boldsymbol{e}} + C_{\boldsymbol{p}} + C_{ml} + C_{pa})}} \right)$$

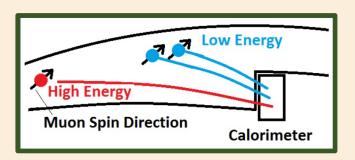
Temperature changes; Injection splash; SiPM recovery time
Use Laser calibration system (in fill and between fills) to track and **correct**







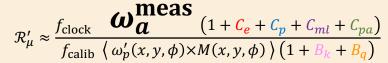
Early-to-late effects - Pileup

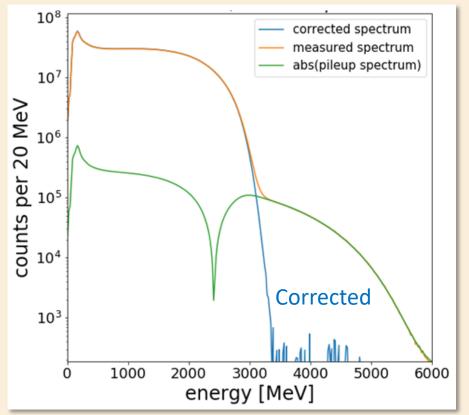


Deduce and subtract pileup spectrum for each dataset

Three methods:

Model based approach (Shadow) Empirical approach PDF approach





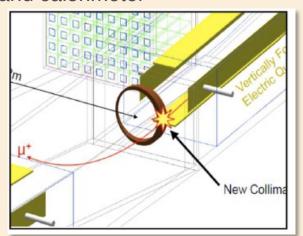


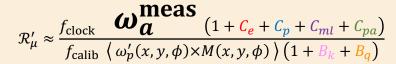
Early-to-late effects - Lost muons

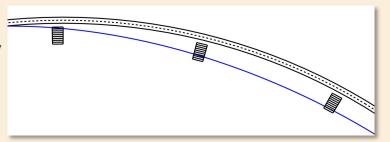
Muon losses lead to time dependence of N

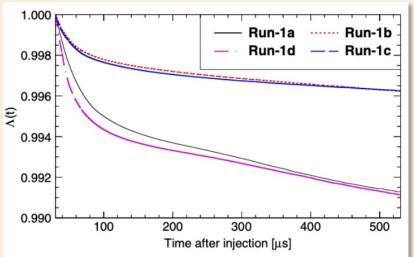
Muon loss term $\Lambda(t) = 1 - K_{\text{loss}} \int_0^t e^{t'/\gamma \tau} L(t') dt'$

Loss spectrum L(t) measured from detecting MIP traces in calorimeters and verified by identifying muons with E/p in stations with tracker and calorimeter





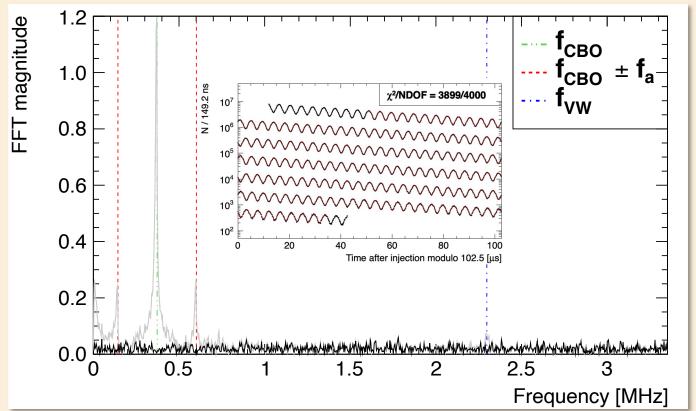






21 parameter fit (again)

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left(\frac{\omega_{\boldsymbol{a}}^{\text{meas}}}{\omega_{\boldsymbol{a}}^{\text{meas}}} \left(1 + \frac{C_e}{c} + C_p + C_{ml} + C_{pa} \right) \right)$$





Checks

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \quad \boldsymbol{\omega_{\alpha}^{\text{meas}}}}{f_{\text{calib}} \left\langle \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \right\rangle \left(1 + B_{k} + B_{q}\right)}$$

Fit results should be stable against fit start time Would show improper modeling of slow effects (e.g. gain) Excellent stability is observed

Also checked fit is independent of

Calorimeter station

Bunch number

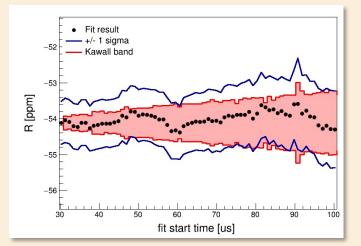
Run number

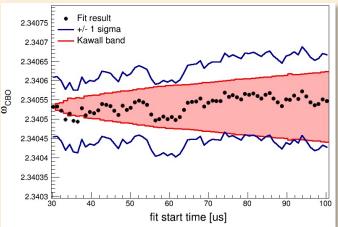
Time of day

Energy bin

Position within calorimeter

. .







Systematics on $\omega_a^{\rm meas}$

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \quad \boldsymbol{\omega_{a}^{\text{meas}}}}{f_{\text{calib}} \left\langle \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \right\rangle \left(1 + B_{k} + B_{q}\right)}$$

Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Gain (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
TOTAL (ppb)	64	70	54	49



Clock blinding

 $\mathcal{R}'_{\mu} \approx \frac{\int \mathbf{clock} \ \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{e}} + C_{p} + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \right\rangle \left(1 + B_{k} + B_{q}\right)}$

Clock detuned $(40 - \epsilon)$ MHz ± 25 ppm

Blinding factor known to only two people outside of collaboration

Checked weekly

Each run is separately blinded





blinding the clock in 2018

Locked Clock Panel





Beam dynamics corrections

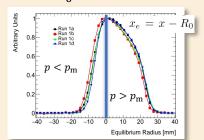
$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{e} + \frac{C_{p}}{f_{\text{calib}}} \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + B_{k} + B_{q}\right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + B_{k} + B_{q}\right)}$$

$$\vec{\omega}_a = -rac{e}{mc} \left[a_\mu \vec{B} - a_\mu \left(rac{\gamma}{\gamma+1}
ight) (\vec{eta} \cdot \vec{B}) \vec{eta} - \left(a_\mu - rac{1}{\gamma^2-1}
ight) (\vec{eta} imes \vec{E})
ight]$$

C_e Electric field correction

Muon beam momentum distribution

$$\Delta p/p = (1-n)\frac{x_e}{R_0}$$
 $C_e = 2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$



Mean x_e and width determined by Fourier analysis of the decoherence rate of incoming bunched beam (6mm, 9mm)

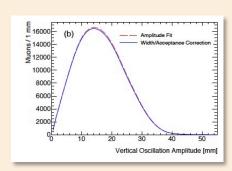
 $C_e \sim 450 \; \mathrm{ppb}$, $\delta_{C_e} \sim 50 \; \mathrm{ppb}$

C_p Pitch correction

From vertical beam oscillations

$$C_p = \frac{n \langle A^2 \rangle}{4 R_0^2}$$

 $\it A$ is vertical oscillation amplitude Measure with trackers and average over $\it \phi$



 $C_p \sim 200 \; \mathrm{ppb}, \delta_{C_e} \sim 20 \; \mathrm{ppb}$

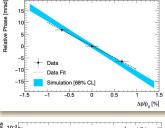
C_{ml} Muon loss correction

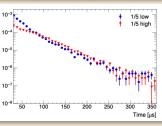
(Muon momentum-phase correlation) + (loss rate depends on momentum) lead to

tiny phase shift

Verify phase-p relation with simulation and changing magnet field

DR collimators used to bias p_u distribution





 $C_{ml} < 20 ext{ ppb}, \delta_{C_{ml}} \sim 5 ext{ ppb}$



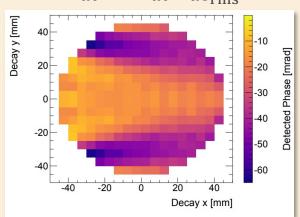
Phase acceptance correction

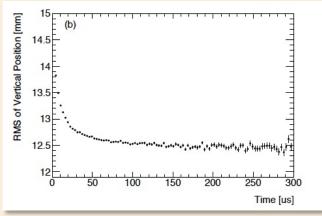
$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{e}} + \frac{C_{p}}{C_{p}} + \frac{C_{pa}}{C_{ml}} + \frac{C_{pa}}{C_{pa}}\right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + \frac{B_{k}}{C_{p}} + \frac{B_{q}}{C_{p}}\right)}$$

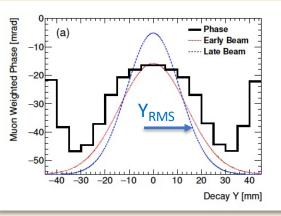
(Beam changing early to late) + (measured phase depending on decay coordinates) lead to...

$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{dY_{\rm rms}}{dt} \frac{d\phi}{dY_{\rm rms}} \neq 0$$

Damaged ESQ resistors exacerbated stability of beam distribution







Extensive use of several simulations (Geant, BMAD, COSY) tuned to data from trackers and calorimeters

 C_{pa} ~ 200 ppb, $\delta_{C_{pa}}$ ~ 80 ppb

Fixing resistors for Run 2 should make $C_{pa} < 50 \text{ ppb}$



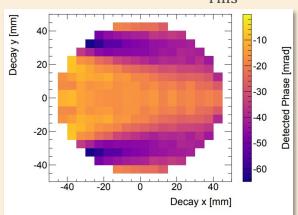
Phase acceptance correction

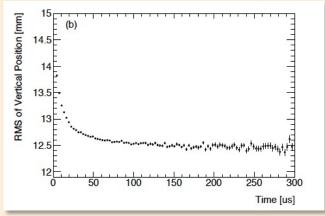
$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{p}} + \frac{C_{p}}{C_{ml}} + \frac{C_{pa}}{C_{pa}}\right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + \frac{B_{k}}{C_{pa}} + \frac{B_{q}}{C_{pa}}\right)}$$

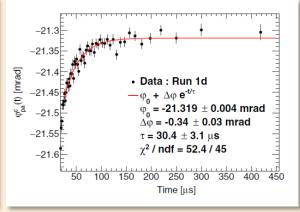
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Measuring the Field (again)

 $\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{p}} + C_{p} + C_{ml} + C_{pa}\right)}{f_{calib} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle^{\left(1 + B_{k} + B_{q}\right)}}$

We need to determine B to < 100 ppb

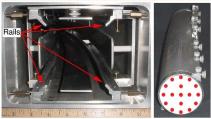
Use NMR probes to measure B in terms of proton precession frequency ω_p

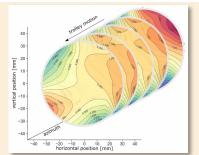
378 fixed probes monitored 24/7



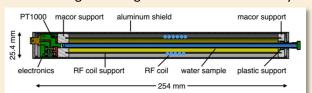


Trolley maps field every 3 days





Trolley cross-calibrated to absolute probes Absolute probes all cross-calibrated in a 1.45 T MRI magnet at Argonne National Laboratory











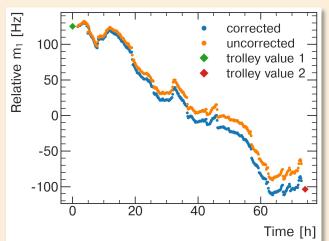
Field Measurement

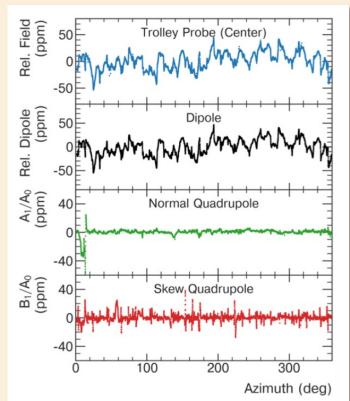
$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{p}} + C_{p} + C_{ml} + C_{pa}\right)}{f_{calib} \, \left\langle \, \boldsymbol{\omega}'_{p}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\phi}) \times \boldsymbol{M}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{\phi}) \, \right\rangle^{\left(1 + B_{k} + B_{q}\right)}}$$

Trolley maps magnetic field in storage region at about 9000 locations over the entire azimuth every 3 days

Fixed probes track field in between trolley runs

Correct with random walk (Brownian bridge) model







Muon weighting

 $\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{p}} + C_{p} + C_{ml} + C_{pa}\right)}{f_{calib} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle^{\left(1 + B_{k} + B_{q}\right)}}$

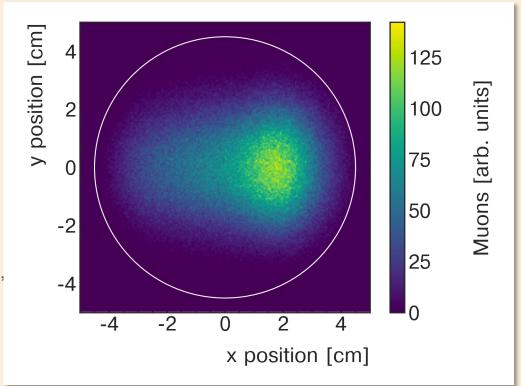
Beam moments are estimated with the trackers

Interpolated field maps averaged over 10s periods and weighted by number of detected positrons

Field and beam moments folded on scale of three hours

Uncertainties from probe calibrations, field maps, tracker alignment and acceptance, calorimeter acceptance, and beam dynamics modeling

$$\delta_{\widetilde{\omega}'_p} \sim 56 \text{ ppb}$$





Kicker transient field

150 ns ~ 200 G kicker pulse produces eddy currents; NMR probes shielded by vacuum chamber wall; Kicker off for trolley runs

Installed a Faraday magnetometer to measure field

$$\mathcal{R}'_{\mu} \approx \frac{f_{\rm clock}\,\omega_a^{\rm meas} \left(1 + \frac{C_e}{C_p} + C_{p} + C_{ml} + C_{pa}\right)}{f_{\rm calib}\,\left\langle\,\omega'_p(x,y,\phi) \times M(x,y,\phi)\,\right\rangle \left(1 + \frac{B_k}{C_p} + \frac{B_q}{C_p}\right)}$$



Fit to exponential for fill fit time

$$B_K\sim 30$$
 ppb, $\delta_{B_K}\sim 40$ ppb



ESQ transient field

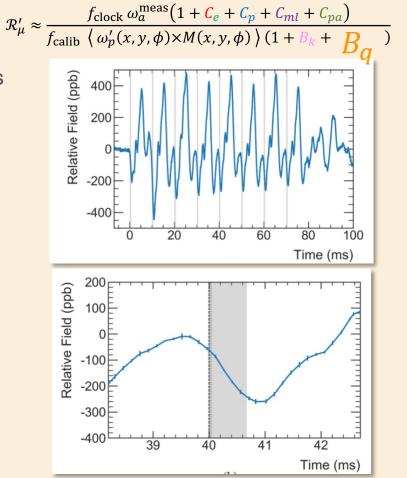
Pulsing quads introduces mechanical vibrations Oscillating conductor perturbs field

Built special NMR probes to map the effect

Averaged over 8 bunches and over 43% of ring with Quad coverage

$$B_q \sim 17$$
 ppb, $\delta_{B_K} \sim 92$ ppb

Uncertainty dominated by incomplete map Expect to reduce x2-3 for Run 2 and after





Corrections & Uncertainties

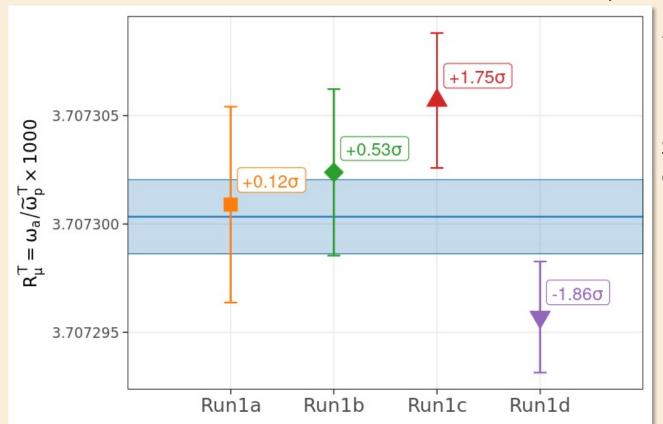
$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{e}} + C_{p} + C_{ml} + C_{pa} \right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + \frac{B_{k}}{B_{k}} + \frac{B_{q}}{B_{q}} \right)}$$

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		434
ω_a^m (systematic)	• • •	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$		56
B_k	-27	37
B_q	-17	92
$\mu_p'(34.7^{\circ})/\mu_e$		10
m_{μ}/m_e		22
$g_e/2$		0
Total systematic		157
Total fundamental factors		25
Totals	544	462



Blinded results

$$\mathcal{R}'_{\mu} \approx \frac{f_{\text{clock}} \, \omega_{a}^{\text{meas}} \left(1 + \frac{C_{e}}{C_{e}} + \frac{C_{p}}{C_{p}} + \frac{C_{ml}}{C_{pa}} + \frac{C_{pa}}{C_{pa}} \right)}{f_{\text{calib}} \, \left\langle \, \omega'_{p}(x, y, \phi) \times M(x, y, \phi) \, \right\rangle \left(1 + \frac{B_{k}}{C_{pa}} + \frac{B_{q}}{C_{pa}} \right)}$$



$$\chi^2$$
/ndf=6.8/3 P(χ^2)=7.8%

Statistical uncertainties dominate, so measurements are largely uncorrelated



Are we ready to unblind (February 25, 2021)?



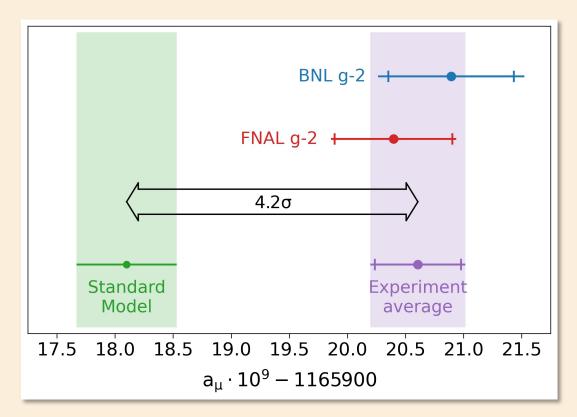


Like landing successfully on Mars





The result and comparison to SM (Announced April 7, 2021)



BNL: 540 ppb Couldn't find anything needing change

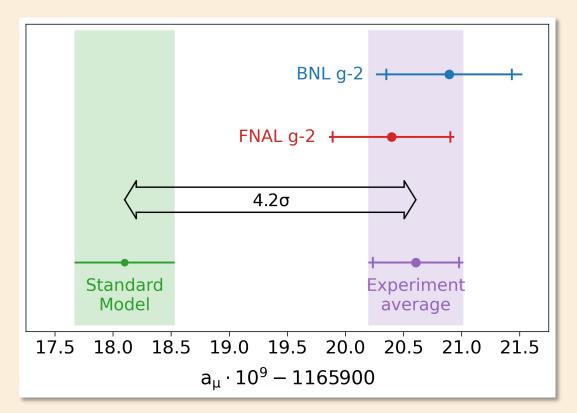
Are we independent?

- New beamline (higher purity)
- New calorimeters (segmented)
- Better shimmed field
- New trackers
- New kickers
- New field metrology
- More powerful simulations
- New people

Analyses are like BNL, but no problems found in past 20 years



The result and comparison to SM



FNAL Run 1

 $a_{\mu} = 116\,592\,040(54) \times 10^{-11}$ (462 ppb)

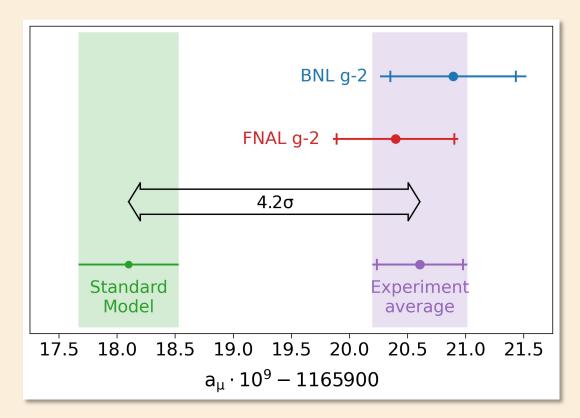
Statistical: 434 ppb

Systematic: 157 ppb

Good agreement with BNL (FNAL 15% smaller uncertainty)



The result and comparison to SM



Combined Experiment

$$a_{\mu} = 116\,592\,061(41) \times 10^{-11}$$
 (350 ppb)

$$a_{\mu}(\exp) - a_{\mu}(SM) = 0.000\ 000\ 002\ 51(59)$$

Significance of tension is 4.2σ

Individual tensions with SM

BNL: 3.7σ

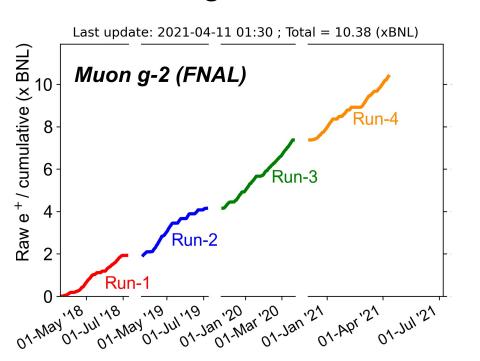
FNAL: 3.3σ



Outlook

Run 1 is 6% of full dataset

Data we have right now



Plan to publish Runs 2+3
Summer 2022
Reduce uncertainty x2
Systematics on track < 100 ppb
Lots of Run 1 problems fixed

We're taking Run 4 now

Planning to reach 20xBNL and yet another 2x reduction in uncertainty

Expect a lot of activity in the Muon g-2 theory initiative too



Read all about it!

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

PRAB

T. Albahri, 30 A. Anastasi^o, 10 K. Badglev, 7 S. Baeßler, 36, a I. Bailev, 17, b V. A. Baranov, 15 E. Barlas-Yucel, 28

T. Barrett, 6 F. Bedeschi, 10 T. Bowcock, 30 G. Canta

A. Chapelain. 6 S. Chari J. D. Crnkovic, 34 S. Dab A. Driutti, 26, 29 V. N. Dugir A. Fiedler,²⁰ A. T. F C. Gabbanini, 10, h M. D. K. L. Giovanetti. 13 S. Haciomeroglu,⁵ T D. W. Hertzog, 37 G. H M. Iacovacci, 9, k M. Inca L. Kelton, 29 A. Keshava B. Kiburg, 7 O. Kim. N. A. Kuchinskiy, 15 K. F. L. Li,^{22, c} I. Logashenk B. MacCoy, 37 R. Mad W. M. Morse, 3 J. Mott, 2 G. M. Piacentino. 25 B. Quinn, 34 N. Raha, 16 L. Santi, 26, d D. Sathya M. Sorbara, 11, q D. Stöck

G. Sweetmore, 31 D. A.

K. Thomson, 30 V

G. Venanzoni, 10 T. Wa

Magnetic Field Measurement and Analysis for the Muon q-2 Experiment at Fermilab

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D. Kawall.⁴¹ L. Kelton.³⁸

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G. Sweetmore, 40 D. A. Sweigart

G. Venanzoni, ¹¹ T. Walton, ⁷

K. Thomson, 39 V. Tishch

T. Bowcock, 39 G. Cantatore, 13, A. Chapelain, S. Charity, Measurement of the anomalous precession frequency of the muon in the Fermilab L. Cotrozzi, 11, 32 J. D. Crnkovic R. Di Stefano, 10, 30 A. Driu C. Ferrari, 11, 14 M. Fert C. Gabbanini, 11, 14 M. D. Gal K. L. Giovanetti, 15 P. C. S. Haciomeroglu,⁵ T. Ha D. W. Hertzog, 48 G. Heske T. E. Chupp, 42 S. Corrodi, 1 L. Cot M. Iacovacci, 10, 31 M. Incagli P. Di Meo, 10 G. Di Sciascio, 12 R L. Kelton, 38 A. Keshavarz M. Farooq, 42 R. Fatemi, 38 C. Ferra B. Kiburg, 7 M. Kiburg, 7, 21 O. I N. S. Froemming, 48, 22 J. Fry, 47 C K. R. Labe, 6 J. LaBour L. K. Gibbons, 6 A. Gioiosa, 29, 11 I. Logashenko, 4, g A. Lorente S. Grant. 36 F. Grav. 24 S. Hacie R. Madrak, 7 K. Makino, 20 A. T. Herrod, 39, d D. W. Hertzog J. Mott.^{2,7} A. Nath.^{10,31} R. Hong, 1, 38 M. Iacovacci, 10, 31 R. N. Pilato, 11, 32 K. T. Pitts, N. Raha, 11 S. Ramachandi N. V. Khomutov. 17 B. Kiburg. 7 M C. Schlesier, 37 A. Schrec A. Kuchibhotla, 37 N. A. Kuchinskiy M. Sorbara, 12, 33 D. Stöcking B. Li. 26, 1, e D. Li. 26, g L. Li. 26, e I G. Sweetmore, 40 D. A. Sweig A. L. Lyon, 7 B. MacCov, 48 R K. Thomson, 39 V. Tis S. Miozzi, 12 W. M. Morse, 3 J.

G. Venanzoni, 11 T. Walton

Muon q-2 experiment

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D. Cauz, 35,8 R. Chakrabortv, 38 S.

PRD

PRA

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm B. Abi, 44 T. Albahri, 39 S. Al-Kilani, 36 D. Allspach, 7 L. P. Alonzi, 48 A. Anastasi, 11, a A. Anisenkov, 4, b F. Azfar, 44 K. Badgley, S. Baeßler, 47, c. I. Bailey, 19, d. V. A. Baranov, 17 E. Barlas-Yucel, 37 T. Barrett, 6 E. Barzi, A. Basti, 11, 32 F. Bedeschi, ¹¹ A. Behnke, ²² M. Berz, ²⁰ M. Bhattacharva, ⁴³ H. P. Binney, ⁴⁸ R. Biorkouist, ⁶ P. Bloom, ²¹ J. Bono, ⁷ E. Bottalico, ¹¹, ³² T. Bowcock, ³⁹ D. Bovden, ²² G. Cantatore, ¹³, ³⁴ R. M. Carev, ² J. Carroll, ³⁹ B. C. K. Casev, ⁷ D. Cauz, 35,8 S. Ceravolo, R. Chakrabortv, 38 S. P. Chang, 18,5 A. Chapelain, S. Chappa, S. Chappa, S. Charitv, 7 R. Chislett, ³⁶ J. Choi, ⁵ Z. Chu, ²⁶, ^e T. E. Chupp, ⁴² M. E. Convery, ⁷ A. Conway, ⁴¹ G. Corradi, ⁹ S. Corrodi, ¹ L. Cotrozzi, 11, 32 J. D. Crnkovic, 3, 37, 43 S. Dabagov, 9, f P. M. De Lurgio, 1 P. T. Debevec, 37 S. Di Falco, 11 P. Di Meo, ¹⁰ G. Di Sciascio, ¹² R. Di Stefano, ^{10,30} B. Drendel, ⁷ A. Driutti, ^{35,13,38} V. N. Duginov. ¹⁷ M. Eads. ²² N. Eggert, A. Epps, J. Esquivel, M. Farooq, R. Fatemi, R. C. Ferrari, M. Fertl, M. Fertl, A. Fiedler, L. A. T. Fienberg, 48 A. Fioretti, 11,14 D. Flay, 41 S. B. Foster, H. Friedsam, F. E. Frlez, 47 N. S. Froemming, 48,22 J. Fry. 47 C. Fu. 26, e C. Gabbanini, 11, 14 M. D. Galati, 11, 32 S. Ganguly, 37, 7 A. Garcia, 48 D. E. Gastler, 2 J. George, 41 L. K. Gibbons, A. Giolosa, 29, 11 K. L. Giovanetti, 15 P. Girotti, 11, 32 W. Gohn, 38 T. Gorringe, 38 J. Grange, 1, 42 S. Grant, ³⁶ F. Grav, ²⁴ S. Haciomeroglu, ⁵ D. Hahn, ⁷ T. Halewood-Leagas, ³⁹ D. Hampai, ⁹ F. Han, ³⁸ E. Hazen,² J. Hempstead,⁴⁸ S. Henry,⁴⁴ A. T. Herrod,³⁹, d D. W. Hertzog,⁴⁸ G. Hesketh,³⁶ A. Hibbert,³⁹ Z. Hodge, ⁴⁸ J. L. Holzbauer, ⁴³ K. W. Hong, ⁴⁷ R. Hong, ^{1,38} M. Iacovacci, ^{10,31} M. Incagli, ¹¹ C. Johnstone, ⁷ J. A. Johnstone, P. Kammel, M. Kargiantoulakis, M. Karuza, J. Kaspar, B. D. Kawall, L. Kelton. Respectively. A. Keshavarzi. 40 D. Kessler. 41 K. S. Khaw. 27, 26, 48, c. Z. Khechadoorian. 6 N. V. Khomutov. 17 B. Kiburg. 7 M. J. Lee, ⁵ S. Lee, ⁵ S. Leo, ³⁷ B. Li, ^{26,1,e} D. Li, ^{26,g} L. Li, ^{26,e} I. Logashenko, ^{4,b} A. Lorente Campos, ³⁸

M. Kiburg, 7, 21 O. Kim, 18, 5 S. C. Kim, 6 Y. I. Kim, 5 B. King, 39, a N. Kinnaird, 2 M. Korostelev, 19, d I. Kourbanis, 7 E. Kraegeloh. 42 V. A. Krylov. 17 A. Kuchibhotla. 37 N. A. Kuchinskiv. 17 K. R. Labe. 6 J. LaBountv. 48 M. Lancaster. 40 A. Lucà, G. Lukicov, G. Luciani, Luc F. Marignetti, 10, 30 S. Mastroianni, 10 S. Maxfield, 39 M. McEvoy, 22 W. Merritt, 7 A. A. Mikhailichenko, 6, a J. P. Miller, S. Miozzi, 12 J. P. Morgan, W. M. Morse, J. Mott, 2, 7 E. Motuk, 36 A. Nath, 10, 31 D. Newton, 39, h

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B. Quinn, ⁴³ N. Raha, ¹¹ S. Ramachandran, ¹ E. Ramberg, ⁷ N. T. Rider, ⁶ J. L. Ritchie, ⁴⁶ B. L. Roberts, ² D. L. Rubin, L. Santi, 35,8 D. Sathvan, H. Schellman, 23,1 C. Schlesier, 37 A. Schreckenberger, 46, 2, 37 Y. K. Semertzidis, 5, 18 Y. M. Shatunov, D. Shemvakin, 4, b M. Shenk, 22 D. Sim, 39 M. W. Smith, 48, 11 A. Smith, 39

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L. Welty-Rieger, M. Whitley, 39 P. Winter, A. Wolski, 39, d M. Wormald, 39 W. Wu, 43 and C. Yoshikawa (The Muon q-2 Collaboration)

PRL

First time Physical Review co-published 4 articles for an experimental result

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